(51) International Patent Classification [7] :		(11) International Publication Number:	**WO 00/25087**
G01B 21/04	**A1**	(43) International Publication Date:	4 May 2000 (04.05.00)

(21) International Application Number: PCT/GB99/03531

(22) International Filing Date: 25 October 1999 (25.10.99)

(30) Priority Data:
9823228.3   24 October 1998 (24.10.98)   GB

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(81) Designated States: JP, US, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) Title: CALIBRATIONS OF AN ANALOGUE PROBE AND ERROR MAPPING
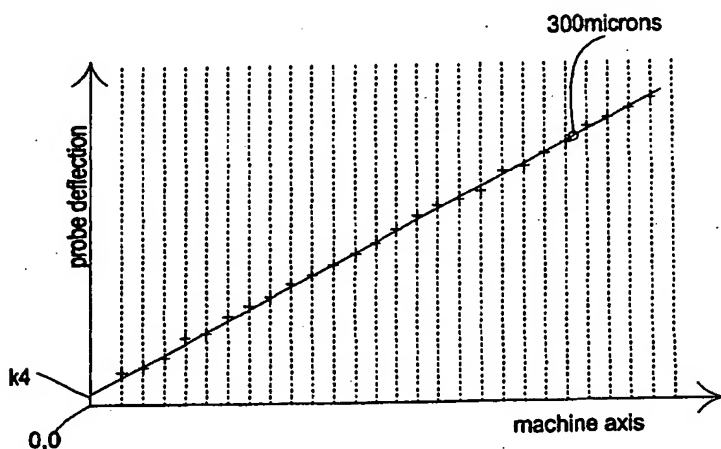
(57) Abstract

     An analogue probe having a stylus with a spherical tip of radius (r) is calibrated using a sphere of known radius (R) mounted on a machine. The stylus tip is driven into the sphere from a plurality of directions (at least 9), each nominally normal to the sphere surface, until the stylus has deflected a predetermined amount. The machine movement is then reversed, and probe (a, b, c) deflection outputs are recorded simultaneously with machine (X, Y, Z) axis positions until the stylus tip leaves the surface. The readings are extrapolated to obtain the (X, Y, Z) readings when the probe radial deflection is zero. The value of (R+r) is determined from these readings along with the position of the sphere centre giving a value with zero probe errors. Values of (R+r) are also determined using a pre–selected radial deflection for each of the directions, by converting probe (a, b, c) outputs at that deflection to incremental machine (X, Y, Z) axis values using a trial probe transformation matrix. The differences in (R+r) values from the value obtained by extrapolation are noted as an error in each case, and the trial probe matrix is then optimised until the errors are minimised. Using the transformation obtained by the calibration, the probe can be error mapped. Relatively immune to errors caused by slippage of the stylus on the surface of the sphere as calibration artefact.

CALIBRATIONS OF AN ANALOGUE PROBE AND ERROR MAPPING

The present invention relates to a method of calibrating
analogue probes. The method has particular reference to
the calibration of analogue probes which have a stylus for

5   contacting a workpiece, and which is mounted on a
mechanical suspension, for example a spring suspension.

Analogue probes of this type are well known and an example
of such a probe is described in our UK Patent No.
1,551,218. This patent describes a probe suspension

10   mechanism which comprises three orthogonally arranged pairs
of parallel springs connected in series between a fixed
point on the probe housing and a movable member to which a
workpiece contacting stylus is connected.

During a measuring operation on a workpiece using such a

15   probe, a machine on which the probe is mounted is driven
towards the workpiece to bring the stylus into contact with
the workpiece surface at various points on the surface.
When the stylus contacts the workpiece the stylus will be
deflected as the machine continues to move, and measuring

20   transducers within the probe generate outputs representing
deflections of the probe stylus along three orthogonal
axes. These axes are referred to as the a,b and c axes of
the probe.

Ideally it would be arranged that the a,b, and c axes of

25   the probe are aligned with the X,Y and Z coordinate axes of
the machine when the probe is mounted on the machine, so
that the measured deflections of the probe stylus will take
place along the X,Y and Z axes of the machine. However,
such alignment is not always possible to achieve.

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Also, if there is any mis-alignment between the three probe
a,b and c axes, such that they are not orthogonal, then
deflection of the stylus, for example, nominally in the a,
direction can give rise to deflections in the b and c

directions also.

Additionally, the scaling factors of the three probe axes,
will, in general, deviate from their nominal values.

Therefore, it is usual to calibrate the probe and machine
5   system to determine the effects of any such mis-alignments
and scaling errors, and thereafter to correct any
measurements made on a workpiece for these effects.

One method of performing the calibration is to mount a
calibration artefact (usually a reference sphere of known
10   diameter) on the machine, and to drive the probe towards
the artefact, for example, along one of the machine axes,
until an increase in the output of the measuring devices of
the probe above a pre-determined threshold level indicates
that contact with the surface of the artefact has been
15   made. After stylus contact has been confirmed, a set of
machine X,Y,Z and probe a,b,c coordinate data are taken.
Machine movement continues until the machine has moved a
selected distance beyond the confirmed contact point, and a
further set of X,Y,Z, and a,b,c coordinate data are taken.

20 . The changes in the a,b,c outputs of the probe's measuring
transducers in the three axes are recorded and correlated
with the changes in the readings of the machine's
measurement devices along each of the three machine axes.
This procedure is repeated for two other orthogonal
25   directions, which may be the other two machine axes, and
from the sets of readings a probe transformation matrix can
be established which relates the probe outputs in the a,b
and c axes to the machine's X,Y and Z coordinate system.
This involves solving the nine simultaneous equations
30   relating the a,b, and c axis data to each of the X,Y, and Z
axes. This process may be repeated for one or more further
deflections but normally only relatively few data points
are taken.

Once the transformation matrix has been established the relevant machine axis components of the probe deflections can be obtained by multiplying the relevant probe output by the relevant matrix term.

5   The key assumption in this calibration is that the machine movement mirrors the probe tip movement. However, this assumption becomes invalid when the stylus slips on the surface of the sphere.

There are two factors which can cause the stylus to slip on
10   the sphere surface;
I) the machine may not go down the commanded direction accurately enough to prevent slippage,
ii) the probe force and deflection vectors may not coincide closely enough to prevent slippage.

15   In accordance with a first novel aspect of the present invention there is provided a method of calibrating an analogue probe which is relatively immune to errors caused by slippage of a stylus on the surface of the calibration artefact. The method therefore allows a more accurate
20   probe transformation matrix to be produced.

In accordance with a second novel aspect of the invention, the above procedure may be carried out in multiple directions (i.e. more than the minimum of three) which facilitates the calculation of a matrix which is more
25   accurate at directions away from the machine axis.

In accordance with another novel aspect of the present invention there is provided a method of error mapping the deflections of an analogue scanning probe.

The methods of the invention will now be more particularly
30   described with reference to the accompanying drawings in which:

Fig 1 illustrates a scanning probe with its stylus in

4

contact with a reference artefact,

Fig 2 shows a plot of probe deflections versus machine
movement in one of the X Y Z axes of the machine,

Referring now to Figs 1 and 2, there is shown an analogue
5   probe 1 mounted on a machine quill (not shown) and which
has a stylus 2 with a stylus ball 3 at its free end. The
stylus is shown in contact with a reference sphere of known
radius R and having its centre O at position X1,Y1,Z1 in
the machine axis coordinates. The stylus ball has a radius
10   r which is to be determined, along with the position of the
centre of the sphere and the probe transformation matrix.

As a first step in the calibration method the probe must be
"zeroed" in its free condition. This simply involves taking
readings from the probe measurement transducers when no
15   contact force is acting on the stylus and setting these to
zero in all three axes, or alternatively storing these
readings so that they can be subtracted from all subsequent
readings.

The next step is to make an estimate of the position of the
20   centre of the sphere, by taking measurements of points at
four positions around the surface of the sphere from which
the position of the centre can be calculated in known
manner, and using a relevant default probe transformation
matrix as a starting point. This step is needed because the
25   calibration method requires the sphere to be contacted at
least at 9 points, but up to as many as may be required
with a reasonable distribution over its surface, taking
account of obstructions, and it is important that the
machine should be driven so the probe will contact the
30   surface at approximately the right positions on the surface
of the sphere. However, it is not important that the
position of the centre of the sphere is known accurately at
this stage.

The calibration method requires that for each of the

plurality of points of the calibration algorithm, the probe
stylus is driven by the machine into contact with the
sphere in a direction which is nominally normal to the
sphere surface. After the stylus ball has contacted the
5   surface of the sphere, the machine continues to drive the
probe in the same direction until the deflection of the
stylus exceeds the required calibration deflection. The
magnitude of this deflection is determined by the
deflections which will occur in practice when the probe is
10   being used to measure a workpiece.

Once the required deflection of the stylus has been
achieved the machine is stopped and reversed along its
approach path, and readings are taken simultaneously at
regular intervals, of the outputs of the measuring devices
15   of the machine and of the measuring transducers in the
probe, to provide the a,b and c outputs of the probe
synchronised with the X,Y and Z coordinates of the machine
position. This process continues until the probe stylus
leaves the surface and for a small distance thereafter to
20   take account of noise and time logs in the probe outputs.

This data may now be used to calculate the X,Y, and Z axis
positions of the machine at zero probe deflection for each
of the points on the sphere, for example, by fitting the
data for each point to an equation of the form;

25                $x = k_1.a + k_2.b + k_3.c + k_4$

and then extrapolating to zero, i.e. $x = k_4$.

Because the reference sphere and the stylus ball are both
specified as being accurately spherical, it follows that
all of these extrapolated points must be on the surface of
30   a sphere of radius R+r. From the points which have been
calculated, the radius R+r and the position of the centre
of the sphere can now be calculated more accurately using a
standard multi-point sphere fit function, for example the
least squares best fit method. Since the radius R of the
35   sphere is known the radius r of the stylus ball can now be

6

determined.

As an alternative to using an "extrapolation to zero"
process with its attendant uncertainties, the data obtained
as the machine is reversed may be interpolated between two
5   points at a very small stylus deflection.

It is to be noted that this part of the calibration process
does not require the use of a probe transformation matrix
since the probe deflection is zero or very small.
Therefore probe errors in the calculation are eliminated or
10   rendered insignificant.

A magnitude of probe deflection is now selected, for
example, 300 microns, which is representative of the
deflections which will be used in subsequent measurements,
and from each of the sets of data, a small number of probe
15   and machine readings on either side of the nominal 300
micron deflection position are averaged and interpolated to
provide estimated X,Y and Z machine axis coordinates and
a,b,c probe outputs at the 300 micron probe deflection
point.

20   A trial probe matrix, for example, the previously used
default matrix is applied to these estimated probe outputs
at the 300 micron radial deflection. Using this trial probe
matrix, the a,b,c probe output values are transformed to
X,Y,Z machine components, which may then be added to the
25   X,Y,Z machine distances for the sphere centre. The radius
of the sphere R+r is calculated for each of the (at least
nine) positions at which calibration data was taken and the
radius errors are stored. An optimisation calculation is
then carried out for each of the coefficients in the probe
30   matrix, by adjusting them until, for example, the root sum
of the squares of the radial errors at the positions is
minimised. Software for carrying out this optimisation
process is known and available from various mathematical
function libraries, and detail is not therefore explained

here.

The optimisation process may include three additional
coefficients representing the position of the centre of the
sphere, in which case at least twelve positions at which
5   calibration data was taken must be used.

The above-described calibration process provides a probe
matrix optimised for one radial deflection of the stylus,
and, if desired, further calculations can be carried out
for other deflections of the probe within the normal
10   measuring range. A basic requirement of the calibration
process is the validity of the assumption that the stylus
ball remains on the surface of the reference sphere while
the data is being gathered at each of the points. It is
also important that the acquisition of the measurement data
15   from the measuring devices of the machine giving the X,Y
and Z coordinates at each point is adequately synchronised
with the data coming from the probe measuring devices which
provide the probe axis a,b and c data.

Once the probe has been calibrated and the probe matrices
20   determined, it is then possible to error map the probe
using the data already collected using an extension to the
above process.

The novel part of the error mapping technique is based on
the realisation that as long as the stylus ball remains in
25   contact with the surface of the reference sphere, while
data is being collected, it is sufficient to map radial
errors only because tangential errors are insignificant for
parts with constant or slowly varying radius of curvature.
This significantly reduces the number of measurements
30   compared with that which would be required to produce a
conventional full error map of the probe's deflections. A
further advantage is that the only apparatus needed to
perform this procedure is an accurate sphere, and these are
commonly available.

8

In order to produce the error map the previously stored
data can be used. The probe outputs in the a,b and c axes
are transformed into machine X,Y and Z coordinate positions
using the probe matrix generated by the calibration method.

5   The radius from the centre of the sphere to the centre of
the stylus tip is calculated. The radius error from the
previously calibrated sum of the known sphere and tip
radii, is stored against the probe deflection magnitude and
the azimuth and elevation angles of the contact point at

10   the 300 micron deflection. Typically the probe deflection
magnitude but not direction is then changed and a second
radial error calculated and stored against the second
deflection magnitude at the same azimuth and elevation
angles.

15   The two probe deflections selected are representative of
the highest and lowest probe deflections likely to be
encountered during a subsequent measuring operation.
However, further data at other probe deflections may be
gathered to improve the certainty of data interpolated from

20   the subsequent error map.

The above process is repeated for further relevant
directions and a map is compiled of radial errors against
azimuth and elevation angles for two deflection magnitudes.
Typically this process generates a map in the form of a

25   part spherical shell of probe deflections. The inner and
outer radii of the shell would normally bracket all
anticipated measuring probe deflection magnitudes and the
azimuth and elevation angle ranges will be selected
relative to the anticipated practical probe deflection

30   directions. For example, if vertical axis bores only are
to be scanned, an elevation angle of 0° would be
sufficient.

Various methods may be used for acquiring the data required
for the error map. These methods include a series of

35   nominally radial movements of the probe stylus towards the

sphere centre at desired positions around the sphere, by
scanning around the sphere at several different constant
deflections, or with continuously varying deflections, by
scanning in one or more planes which may be parallel,
5   orthogonal or angled, or by any combination of these
techniques. The map itself may consist of a multi-
dimensional look-up table of radial errors versus
deflection magnitude, azimuth and elevation angles, or it
may consist of a function with associated polynomial
10   coefficients, or a trigonometrical function.

If the map is in the form of a look-up table then
subsequent measurement errors are corrected by
interpolating the stored radial error values to acquire the
correction to be applied to the stylus tip position at the
15   measured position. Alternatively if the map is a
polynomial function the radial error expression is solved
for the deflection magnitude and angles at the measured
position.

It has been found that friction between the stylus tip and
20   the surface of the sphere can cause additional errors which
need to be taken account of in the error map. In practice
we have found that friction causes the probe deflection
vector to be at some angle from the outward normal from the
surface of the sphere. This may be any positive or
25   negative angle up to the maximum angle of friction,
depending on the direction of movement of the probe tip
relative to the sphere. We have found that the measuring
errors increase as the friction coefficient increases, and
with the amount of asymmetry in the errors of the probe a,b
30   and c axes. For example, at a radial deflection of 1mm
with a friction angle of 8.5° and an asymmetry in the a and
b axes of 3% a normal error of 2.5 microns can be present.

The coefficient of friction of the probe tip varies
according to the material and condition of the contacted
35   workpiece surface, and will almost certainly differ from

that of the calibration/mapping artifact.

Since it is difficult to predict or control the coefficient
of friction, in a further novel refinement to the error
mapping process, we have found that the current angle of
5   friction can be determined to a first order by comparing
the probe deflection vector direction with the measured
surface normal direction (this being derived from the
actual probe tip locus). Although this value of friction
angle is inaccurate because it is derived from the probe
10   outputs the errors of which are being mapped, it is
accurate enough to enable a first order improvement in the
accuracy of the error map.

In an additional step therefore in the method of creating
the error map it is proposed that the reference sphere
15   should be scanned both clockwise and anti-clockwise and
the apparent angle of friction determined from the
difference in the probe deflection vector and the surface
normal direction. Then, in addition to the stored
correction value, which is preferably calculated for zero
20   coefficient of friction, the value of the rate of change of
correction with friction angle is also stored for each
azimuth elevation and radial deflection. Subsequent
measurements can then be corrected by an amount found by
interpolating the stored correction value and adding it to
25   the interpolated rate of change multiplied by the current
coefficient of friction (determined as previously from the
probe deflection vector direction and the measured surface
normal direction).

We have found that by including this allowance for the
30   angle of friction, the radial measuring errors can be
reduced to sub-micron level.

CLAIMS

1.   A method of calibrating an analogue probe having a
stylus with a workpiece-contacting tip of radius (r)
comprising the steps of:

5   a)   mounting the probe and a calibration sphere of known
radius (R) on a machine,

b)   causing relative movement between the probe and the
sphere from a plurality of directions each of which is
nominally normal to the surface of the sphere to bring the
10   stylus tip into contact with said surface and deflect the
stylus by a predetermined amount,

c)   reversing the relative movement and recording
simultaneous values of the radial deflections of the stylus
and of machine axis X,Y and Z positions at intervals at
15   least until the stylus tip leaves the surface,

d)   extrapolating each of the recorded sets of readings to
obtain values of the machine X,Y and Z axis positions when
the stylus radial deflection is zero,

e)   calculating from the extrapolated machine axis
20   positions the value (R+r) and the position of the centre of
the sphere,

f)   at a pre-selected radial deflection of the stylus
which is the same for each of the directions noting the a,b
and c outputs of the probe, and, using a trial probe
25   transformation matrix converting the probe a,b and c values
into incremental X,Y and Z values of machine axis
positions,

g)   using the calculated position of the centre of the
sphere, determining the radius of the sphere (R+r) as
30   measured in each of the directions,

h)   noting the differences in the radius measurements in each of the directions compared to the radius as determined in step (e) and,

i)   optimising the probe transformation matrix to minimise
5   the differences in the calculated radius values.

2.   A method of calibrating an analogue probe having a stylus with a workpiece-contacting tip of radius (r) comprising the steps of:

a)   mounting the probe and a calibration sphere of known
10   radius (R) on a machine,

b)   causing relative movement between the probe and the sphere from a plurality of directions each of which is nominally normal to the surface of the sphere to bring the stylus tip into contact with said surface and deflect the
15   stylus by a predetermined amount,

c)   reversing the relative movement and recording simultaneous values of the radial deflections of the stylus and of machine axis X,Y and Z positions at intervals at least until the stylus tip leaves the surface,

20   d)   interpolating each of the recorded sets of readings to obtain values of the machine X,Y and Z axis positions when the stylus radial deflection is close to zero,

e)   calculating from the interpolated machine axis positions the value (R+r) and the position of the centre of
25   the sphere,

f)   at a pre-selected radial deflection of the stylus which is the same for each of the directions noting the a,b and c outputs of the probe, and, using a trial probe transformation matrix converting the probe a,b and c values
30   into incremental X,Y and Z values of machine axis

13

positions,

g) using the calculated position of the centre of the sphere, determining the radius of the sphere (R+r) as measured in each of the directions,

5 h) noting the differences in the radius measurements in each of the directions compared to the radius as determined in step (e) and,

i) optimising the probe transformation matrix to minimise the differences in the calculated radius values.

10 3. A method of error mapping an analogue probe having a stylus with a workpiece-contacting tip of radius (r) comprising the steps of:
calibrating the probe in accordance with the method as claimed in claim 1 or claim 2,
15 using the probe transformation matrix generated by the calibration step, transforming probe a,b and c output data at least at two different radial deflections of the probe for one contact point on the sphere into machine X,Y and Z coordinate positions,
20 calculating the radius R+r for each deflection magnitude,
repeating the calculation for at least two radial deflections at other positions around the sphere,
comparing the calculated radii from the previously
25 calibrated value and noting the radial errors in each case,
storing the radial errors against the respective values of deflection and the azimuth and elevation of the contact point to form the error map.

4. A method of error mapping an analogue probe as claimed
30 in claim 3 and comprising the further steps of:
determining the angle of friction between the probe tip and the reference sphere,
correlating the variation in the error values with the

14

variation in friction angle, and

storing this variation as an additional term in the error map.

Fig1

Fig2
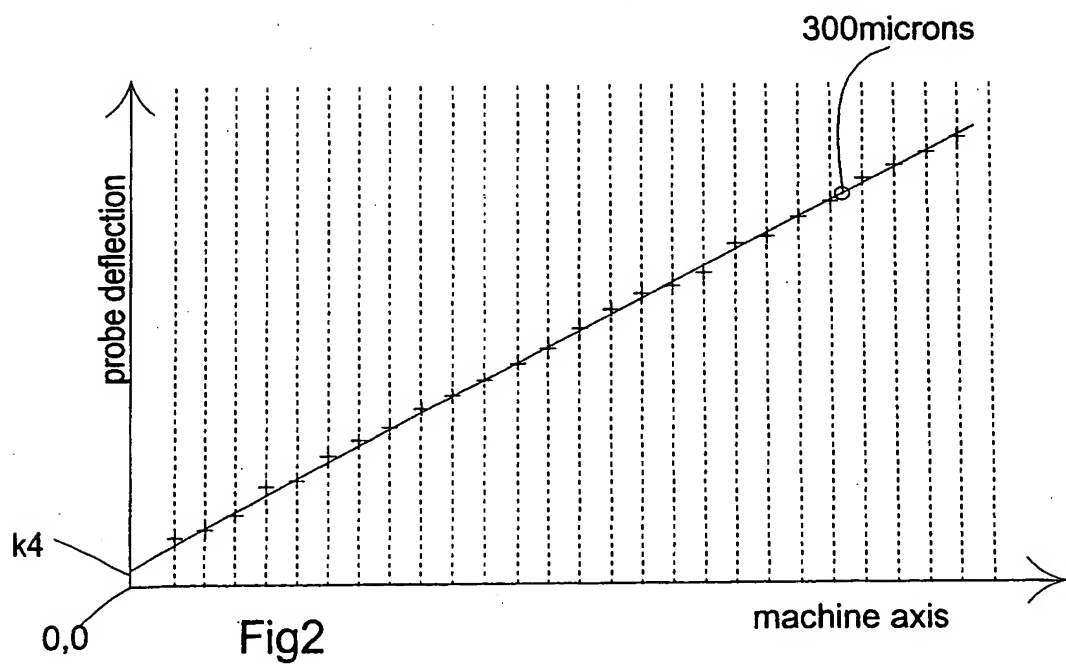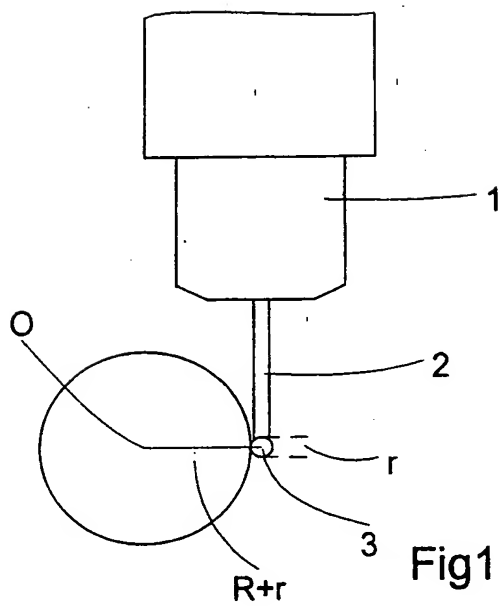
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7   G01B21/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7.   G01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 599 513 A (RENISHAW) 1 June 1994 (1994-06-01) column 4, line 16 - line 28; figure 3	1-4
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A	US 4 875 177 A (RENISHAW) 17 October 1989 (1989-10-17) figure 1	
A	DE 44 39 578 C (LEITZ) 8 February 1996 (1996-02-08) column 2, line 68 -column 3, line 9; figures 1,3	

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
25 January 2000	08/02/2000

Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Mielke, W

Form PCT/ISA/210 (second sheet) (July 1992)

1

International Application No

PCT/GB 99/03531

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